

## A THREE-DIMENSIONAL VIRTUAL SIMULATOR FOR AIRCRAFT FLYOVER PRESENTATION

*Stephen A. Rizzi and Brenda M. Sullivan*

Structural Acoustics Branch  
NASA Langley Research Center  
Hampton, VA 23681

*Christopher A. Sandridge*

Analytical & Computational Methods Branch  
NASA Langley Research Center  
Hampton, VA 23681

{stephen.a.rizzi,brenda.m.sullivan,christopher.a.sandridge}@nasa.gov

### ABSTRACT

This paper presents a system developed at NASA Langley Research Center to render aircraft flyovers in a virtual reality environment. The present system uses monaural recordings of actual aircraft flyover noise and presents these binaurally using head tracking information. The three-dimensional audio is simultaneously rendered with a visual presentation using a head-mounted display (HMD). The final system will use flyover noise synthesized using data from various analytical and empirical modeling systems. This will permit presentation of flyover noise from candidate low-noise flight operations to subjects for psychoacoustical evaluation.

### 1. INTRODUCTION

NASA Langley Research Center has a long record in psychoacoustic studies of aircraft flyover noise. Such studies require human subjects to listen to flyover sounds and to rate them according to various scoring methodologies. Two methods of presenting the flyovers are available: field tests and laboratory tests. Field tests using real aircraft flying over the subjects are problematic because exactly what each listener is hearing is unknown, the same flyover can never be reproduced exactly, and flight tests are extremely expensive.

Therefore, NASA Langley has historically presented flyover recordings or syntheses for evaluation using loudspeakers in laboratory listening situations. The outdoor environment has been represented by an anechoic room or an auditorium with up to 10 speakers in the walls and ceiling [1-4]. Such laboratory situations allow much more control of the test conditions than field testing. Signals can be replayed exactly the same many times, the same sound can be played at different levels, and aircraft sounds of the future can be synthesized. However, the artificial laboratory setting reduces the credibility of the results. If a flyover sound is presented from a loudspeaker in front of the subject, then there is no spatial feel. If the sound is presented from overhead speakers, then the sound comes from the right direction, but the complete range of a flyover is very difficult to simulate realistically.

One method for helping to establish the presence lacking in the laboratory test is the use of binaural recordings made with a dummy mannequin in a field test, played back to subjects over headphones. While such an approach gives a convincing presence, playback is limited to the orientation in which the recording was made. Thus, the illusion of presence is spoiled

because subjects often wish to localize the sound source both visually and aurally, as they would in the real world.

In an attempt to retain a controllable test environment, yet more closely recreate conditions in the field, a new capability has been developed which allows subjects to be immersed both visually and aurally in a three-dimensional, exterior virtual environment. With the aid of head tracking (real-time measurement of a listener's head orientation), real time graphics rendering and binaural simulation allow the presence to be maintained as the subject interacts with the test environment. The binaural simulation presently makes use of monaural recordings at predetermined listener positions. The intent, however, is to utilize the simulation approach described herein with synthesized flyover noise so that future subjective testing of low-noise flight operations may be performed. The remainder of this paper discusses the method by which binaural simulation of recorded flyover noise is performed, the real-time implementation, and an outline of future directions.

### 2. BINAURAL SIMULATION OF AIRCRAFT FLYOVER NOISE

The strategy adopted is centered on the listener position, that is, the binaural simulation starts with monaural aircraft flyover noise defined at a stationary listener position. The listener's orientation, but not position, is then permitted to change. From a practical standpoint, this permits the use of sound recordings made at the listener position(s), as opposed to recordings made nearer to the flying source. Further, it simplifies the simulation considerably as noise source directivity, spreading loss, atmospheric attenuation, and Doppler shift are automatically realized in the recording. When using synthesized flyover noise, these effects must be accounted for in the synthesis. Thus, the approach outlined below is independent of the content origin.

#### 2.1. Emission Trajectory Calculation

To simulate the position of the aircraft in a three-dimensional space, knowledge of both the listener and aircraft position and orientation must be known as a function of time. For subjective testing purposes, a fixed listener position with variable orientation is desired. Listener head orientation is measured with a 3-DOF tracker. Since the sound used in the simulation is specified at the listener position, the directivity of the noise source is already taken into account. Further, because the

aircraft is far enough away from the listener, it may be treated as a point source. Thus, only the aircraft position, not its orientation, is required. In the case of recorded flyover noise, aircraft position as a function of time is measured by GPS or other means and recorded at sufficiently short, uniform time intervals (typically every 0.5s). Simultaneous microphone measurements are made at one or more listener positions. The aircraft location and recordings are synchronized through a master clock. In the case of synthesized flyovers, all such information is specified as part of the synthesis process. A typical flight trajectory is shown in Figure 1. A listener position is represented by the lollipop. The passage of time is implicit in the trajectory, and typically is on the order of several minutes for the pattern shown.

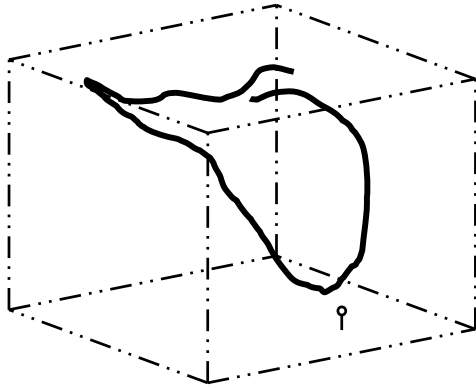


Figure 1: Typical aircraft flight trajectory.

Trajectory data synchronized through a master clock with the sound recording indicates the aircraft visual position at the time the recording is made. However, it is the emission position, not the visual position, which must be used to accurately simulate the location of the sound source in three-dimensional space. The two are different because the speed of light ( $2.998 \times 10^8$  m/s) is much greater than the speed of sound  $c$  (331 m/s @ sea-level on a standard day). Thus, the emission position lags the visual position along the trajectory by a retarded time proportional to the distance between the visual position and the listener, i.e.,

$$t_i = \tau_i + r_i / c \quad (1)$$

where  $t_i$  is the sound arrival time corresponding to the  $i^{\text{th}}$  trajectory point,  $\tau_i$  is the time of the  $i^{\text{th}}$  trajectory point, and  $r_i$  is the distance between the  $i^{\text{th}}$  trajectory point and the listener. (Note that this calculation must be performed for each listener position since  $r_i$  is different in each case.) What follows from

(1) is the emission trajectory  $(t_i, x_i, y_i, z_i)$ . Common to it and the original (visual) trajectory  $(\tau_i, x_i, y_i, z_i)$  is the sequence of positions. Only the time differs. However, unlike the uniform time interval in the visual trajectory, the time interval in the emission trajectory is not uniform. In order to deal with a single time-base and to have finely spaced positions, both trajectories are interpolated at a uniformly small time interval, typically 50ms. An example of the visual and emission trajectories for the altitude component  $z$  is shown in Figure 2. The delay time is

seen to be smallest at the closest position (corresponding to about 180s).

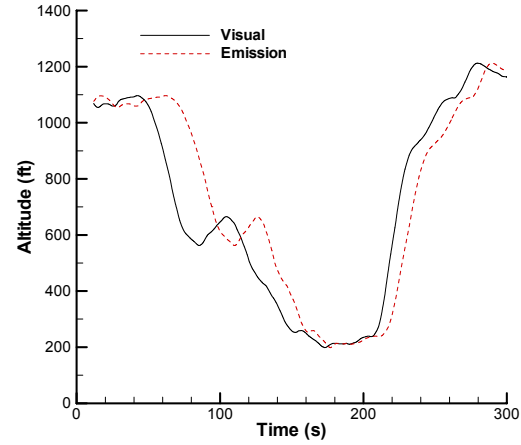


Figure 2: Emission and visual flight trajectories.

## 2.2. Real-Time Binaural Simulation

Real-time binaural simulation is performed in the time-domain using continuously updated head-related impulse response (HRIR) filter pairs. Because the flyover noise is either measured or synthesized at the listener position, distance and velocity related effects such as spreading loss, atmospheric attenuation, and Doppler shift are automatically taken into account. Selection of HRIR filters is thus based upon only the relative orientation of the listener to the emission trajectory. The emission trajectory is determined from above for each fixed listener location. Listener head tracking is used to determine the head orientation. The binaural audio stream is rendered to the listener over headphones.

## 3. SYSTEM IMPLEMENTATION

A real-time virtual reality system for presenting aircraft flyovers was developed using a combination of custom application software and commercial off-the-shelf hardware/software. A portable version is shown schematically in Figure 3. The 3D audio subsystem operates on a client-server architecture. An OpenGL Performer™ 2.5 [5] graphics simulation application written using the CAVELib™ 3.0 immersive API [6] acts as the both the graphics server and the 3D audio client. This graphics application environment was selected because it allows an identical code base to be run across various computer architectures, operating systems, and visual display environments. The aircraft flyover simulator application has been run on graphics servers ranging from a high-end graphics, Linux laptop displaying stereo graphics to a head-mounted display (as shown), to an SGI Onyx 2 InfiniteReality™ computer displaying stereo graphics to a Cave Automated Virtual Environment (CAVE™) [7]. Listener orientation tracking is performed by the trackd™ 5.0 daemon application [8] on the graphics server. This information is used by the graphics server

for control of the proper visual perspective and by the audio server for HRIR selection.

In general, source and head position and orientation information is passed from the audio client to the audio server via a hardware interface for filter updating. The audio source content is resident on the audio server. In order to support different 3D audio servers in a manner transparent to the client application, a high level 3D audio wrapper library was written to insulate the application from the details of the particular audio server in use. At present, this wrapper library utilizes the AuClient library for communication with the AuSIM GoldServer™ audio server [9] and the SNAP library for

communication with the Lake Huron server [10]. Audio client commands in the wrapper library include main control functions for server initialization and termination, transport functions (play, stop, rewind), and positioning functions for the listener and sources. All necessary coordinate transformations are handled automatically. For the aircraft flyover simulator application, the GoldServer series of 3D audio servers was selected because of its ability to handle long audio wavefiles, the ability to override the spreading loss, and a new sequencing feature (to be described next), which allows the emission trajectories to be loaded *a priori*.

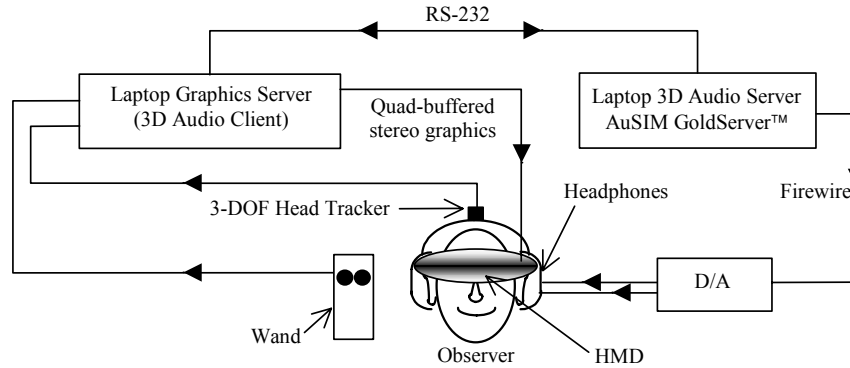


Figure 3: Schematic of the portable aircraft flyover simulator.

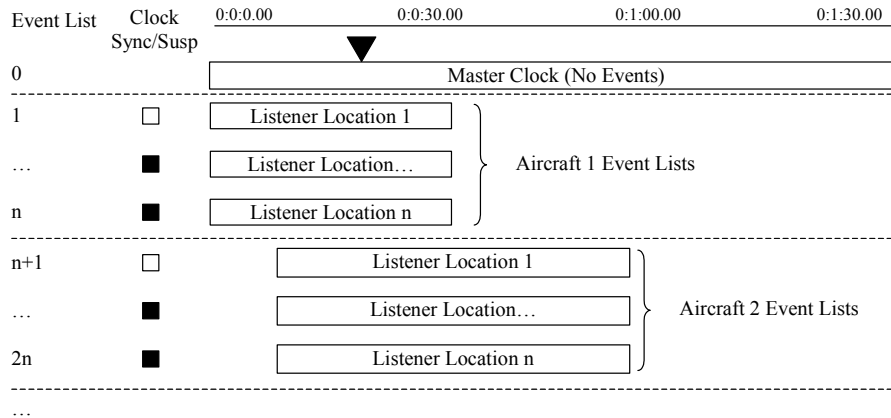


Figure 4: Notional depiction of event sequencer implementation.

### 3.1. Source Event Sequencing

To meet the as-yet undefined requirements of future subjective tests, it was desired to develop the simulator in a way which permitted an arbitrary number of simultaneous or overlapping aircraft flyovers at an arbitrary number of listener positions. While the rendering engine of the GoldServer is capable of filtering more sources than would be of practical interest in this application, real-time client side updates of the source location over RS-232 is bandwidth limited.

Recall that the emission trajectory is known *a priori*. The aircraft flyover noise from a pre-determined trajectory is presented to the listener. The listener only has the ability to change his orientation, not the trajectory of the aircraft. Therefore, to circumvent the potential RS-232 bottleneck, this

information can be downloaded to the server before the simulation begins. Then, only the listener orientation needs to be updated over RS-232. NASA contracted the development of an event sequencer to AuSIM, Inc. for the GoldServer engine.

The event sequencer can be considered as a multi-track MIDI sequencer, except that each track has its own clock. Clocks may be run independently or be synchronized. Within each track is a sequence of time stamped events, e.g. source locations. Processing of an event sequence may be suspended by setting its clock at a particular value, in effect muting the track.

A notional depiction of how the event sequencer is implemented in the aircraft flyover simulation is shown in Figure 4. Event list 0 contains no events. Its clock, however,

acts as a master clock and is synchronized with a clock running on the graphics server. As shown, there are  $n$  listener locations associated with each aircraft, each with its own event list. Within each event list is a unique sequence of emission position points corresponding to that listener location-aircraft trajectory pair. In addition, each event list contains the equivalent of a start playback command. As depicted, listener location 1 is active (only one location should be active at a time) and two aircraft flyovers are being simulated.

Utilization of the event sequencer simplifies client side application programming. To switch from one listener location to another, the existing event list clocks are suspended and the new clocks are synchronized to the master. To skip from one time in the simulation to another, the master clock is updated to the desired time and the active event list clocks are synchronized to it. A search-back feature was implemented on the audio server, so sample playback will begin mid-stream if necessary when skipping forward and back in time.

#### 4. SIMULATOR DEMONSTRATION

Recordings from a series of flight tests conducted at Wallops Island, Virginia [11], were used in the development of the simulator. Two recording locations were used for each of four aircraft (Beech KingAir, Dassault Falcon 2000, McDonnell Douglas DC-9, and a Boeing 767). Three-dimensional graphics models of each and representative landscapes were used in the graphics simulation. When performing future subjective testing, an appropriate landscape (e.g. suburban) will be used, as the noise environment away from the airport will be the subject of investigation.

In addition to physically moving his head, the listener may also rotate the scene and toggle between one position and another with a wand input device, see Figure 3. The simulator also has the capability of simultaneously displaying the aircraft visual and emission positions. This feature has excellent educational and debugging value. The extent to which these user interfaces will be exposed in the subjective test environment remains to be determined.

#### 5. CLOSING REMARKS

A new capability has been developed for the immersive simulation of aircraft flyovers. The use of head tracking allows the illusion of visual and aural presence to be maintained as the subject interacts with the environment. The system architecture allows the simulation to be performed across a wide range of platforms. Further, a versatile 3D audio client wrapper library and implementation of a new event list sequencer both simplify application development and improve the performance of the simulation application.

Before subjective testing is performed, two additional developments must be made. One is to customize the operator and subject interface. The other is to synthesize flyover noise using data from community noise prediction codes [12]. The challenge here is to convert time-averaged frequency domain predictions to a pressure time history at the observer location. An earlier synthesis code [13] will serve as the basis for the new

program. This will allow the investigation of candidate low-noise flight paths over communities without the expense of dedicated flight tests, and will allow the study of noise from aircraft not yet in existence.

#### 6. WEB RESOURCES

Examples of the system's capabilities in the form of AVI movies are available at <http://stabserv.larc.nasa.gov/>.

#### 7. REFERENCES

- [1] McCurdy, D.A. and Powell, C.A., "Annoyance caused by propeller airplane flyover noise," NASA TP 2356, August 1984.
- [2] McCurdy, D.A., "Annoyance caused by advanced turboprop aircraft flyover noise, single-rotating-propeller configuration," NASA TP 2782, March 1988.
- [3] McCurdy, D.A., "Annoyance caused by advanced turboprop aircraft flyover noise, counter-rotating-propeller configuration," NASA TP 3027, September 1990.
- [4] Leatherwood, J.D. and Sullivan, B.M., "A laboratory study of subjective annoyance response to sonic booms and aircraft flyovers," NASA TM 109113, May 1994.
- [5] Eckel, G. and Jones, K., "OpenGL Performer Programmer's Guide," Silicon Graphics, Inc., 2000.
- [6] "CAVE Library User's Guide," VRCO, Inc., 2002.
- [7] Cruz-Neira, C., Sandin, D.J., and DeFanti, T.A., "Surround-screen projection-based virtual reality: The design and implementation of the CAVE," *ACM SIGGRAPH 93 Conference Proceedings*, pp. 135-142, 1993.
- [8] "Trackd User's Guide," VRCO, Inc., 2002.
- [9] "GoldServe, AuSIM3D Gold Series Audio Localizing Server System, User's guide and reference," AuSIM Inc., Palo Alto, CA, November 1999.
- [10] "Huron technical manual (revision 5.0)," Lake Technology Limited, Sydney, Australia, February 2000.
- [11] Senzig, D.A., Fleming, G.G., and Shepherd, K.P., "Measured engine installation effects of four civil transport airplanes," *NOISE-CON 2001 - 2001 National Conference on Noise Control Engineering*, Portland, Maine, 2001.
- [12] Gillian, R.E., "Aircraft noise prediction program user's manual," NASA TM-84486, January 1983.
- [13] McCurdy, D.A. and Grandle, R.E., "Aircraft noise synthesis system," NASA TM-89040, February 1987.